SOME MEASURED CHARACTERISTICS OF SEVERE STORM TURBULENCE

By Roy Steiner and Richard H. Rhyne

NASA Langley Research Center
Langley Air Force Base, Va.

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SUMMARY

Measurements of atmospheric turbulence obtained from airplane flights through severe storms in connection with the National Severe Storms Project will be discussed. Various characteristics of turbulence, such as differences in intensity between storms and the turbulence intensity with altitude and time will be indicated. These measurements for severe storm conditions will also be compared with other measurements for clear-air and nonstorm weather conditions as a means of illustrating the relative severity of turbulence for various flight conditions. For these purposes, both derived gust velocities and power spectra of atmospheric turbulence will be used. The detailed nature of the vertical and horizontal flow patterns and the variations in atmospheric pressure as measured during several airplane traverses through storm centers will also be discussed.

INTRODUCTION

The National Aeronautics and Space Administration has actively participated in the National Severe Storms Project during the past 2 years of its operation. This participation has consisted of the measurement of the turbulence within the storms and was motivated by a twofold objective. First, the turbulence data furnish information for the use of the NSSP in the study of the life cycle and dynamics of severe local storms. Secondly, the detailed measurements of severe turbulence are of considerable value for use in the design and operation of aircraft.

The turbulence measurements have been accomplished during the 1960 and 1961 seasons through the close cooperation of the U.S. Air Force which provided the airplane and support and operating personnel. During the past 2 years of operations, surveys of thunderstorms at both subsonic and supersonic speeds were made and measurements of the turbulence characteristics of the storms in various stages of development obtained. These measurements represent the first time that detailed turbulence data suitable for spectral analysis have been obtained in severe storm conditions.

*Aerospace Technologist.

The purpose of this paper is to discuss the measurements from several storm surveys from the first year's operations. These results, which represent three storms investigated during the 1960 operations, include examples of the magnitude and characteristics of the vertical and horizontal components of the turbulence, the intensity of the turbulence within the clouds, and an indication of the pressure changes within the storms.

SYMBOLS

a_n normal acceleration, g units or ft/sec^2

g acceleration due to gravity

l distance from accelerometer to angle-of-attack and angle-of-sideslip vanes, ft; also wavelength, ft

$R_x(\tau)$ auto-covariance function

t time, sec

T specified time, sec

V true airspeed, ft/sec

w_a airplane vertical velocity, ft/sec

w_g vertical component of gust velocity, ft/sec

v_g lateral component of gust velocity, ft/sec

x arbitrary input disturbance

α_v vane-indicated angle of attack, radians

θ pitch angle, radians

$\dot{\theta}$ pitch velocity, radians/sec

Φ_x power spectral density function

σ root-mean-square deviation

σ_{w_g} root-mean-square deviation of vertical component of gust velocity, ft/sec

τ	time lag, sec
ω	frequency, radians/sec
U_{de}	derived gust velocity, defined in reference 1 as $\frac{2a_{n_{max}}W}{m\rho_o S V_e K_g}$
K_g	gust factor
m	wing lift-curve slope, per radian
$a_{n_{max}}$	maximum value of normal acceleration, g units
ρ_o	air density at sea level, slugs/cu ft
S	wing area, sq ft
W	airplane weight, lb
V_e	equivalent airspeed, $V\sqrt{\rho/\rho_o}$, fps
ρ	air density, slugs/cu ft
Ω	reduced frequency, equal to ω/V, radians/ft
"D"	actual altitude minus pressure altitude, ft
—	a bar over a symbol denotes a mean value

BASIC TURBULENCE MEASUREMENTS

Before proceeding to a discussion of the turbulence and other cloud parameters, it is well to consider briefly the two basic methods used to measure and describe atmospheric turbulence. The two methods are referred to as the discrete gust and the continuous turbulence or power spectral density method and are illustrated in figure 1.

The discrete gust method has been used for many years to provide a relatively simple means of defining the magnitude and frequency of occurrence of gusts. The values of derived gust velocities U_{de} are used primarily in loads calculations as a means of transferring the acceleration measurements on one airplane to another. The basic measurements used in this method are the peak accelerations at the center of gravity of the airplane. Values of derived gust velocities are computed from the following equation, which is also given in figure 1:

$$U_{d_e} = \frac{2a_{n_{max}}\frac{W}{S}}{m\rho_o V_e K_g} \tag{1}$$

The derivation of the derived gust equation (eq. (1)) is given in reference 1 and is based on the solution of an equation of airplane vertical motion in an isolated gust. The principal assumptions made are: (1) the airplane is a rigid body, (2) the airplane forward speed is constant, (3) the airplane is in steady level flight prior to entry into the gust, and (4) the airplane can rise but cannot pitch. The "isolated" gust is designated as having a (1 - cos) shape, as illustrated in the left side of figure 1, in which the gust velocity increases from zero to the maximum value in 12.5 wing chord lengths. The gust velocities computed from equation (1) are frequently presented in terms of average numbers of gusts per mile of flight which exceed given values as illustrated in the lower left portion of the figure.

The continuous turbulence or power spectral density method has been developed as a means of providing a more fundamental description of atmospheric turbulence. The basic measurement for this method is the angle of attack measured by a flow vane or a differential pressure probe ahead of the airplane as sketched in figure 1. The angle-of-attack measurements are corrected for effects of airplane motions, pitch attitude θ, vertical velocity of the airplane w_a, and pitching velocity $\dot{\theta}$, to provide a continuous time history of the true gust velocity w_g, as given by the following equation:

$$w_g = V\alpha_V - V\theta + w_a + l\dot{\theta} \tag{2}$$

where V is true airspeed and l is the distance between the accelerometer and the angle-of-attack vane. All of the quantities are measured directly except w_a, which is determined from an integration of the accelerometer measurements. Equation (2) as used in the evaluation of the vertical component of gust velocities is based on the following assumptions:

(1) All disturbances are sufficiently small so that the angle in radians may be used in place of the sine of the angle.

(2) Boom bending is negligible.

(3) Effects of variation in upwash on vane indicated angle of attack are negligible.

The measurements are normally taken as increments from the mean values for the entire record. The actual evaluation procedures to obtain the time history of the vertical component of gust velocities are given by:

$$w_g = V(\alpha_v - \bar{\alpha}_v) - V(\theta - \bar{\theta}) + \int_0^T (a_n - \bar{a}_n)dt + l(\dot{\theta} - \bar{\dot{\theta}}) \tag{3}$$

where the bar, $^-$, indicates the average value for the record length to be evaluated. This evaluation yields a time history of the true gust velocity in continuous turbulence determined at equally spaced time intervals. For the evaluations included herein, the time interval was 0.05 second.

This time history is then analyzed to determine the power spectrum of turbulence as illustrated in the lower right-hand portion of figure 1. The procedures used in the determination of the power spectra are essentially the same as those outlined in references 2 and 3. The power spectrum of a disturbance $x(t)$ is defined by

$$\Phi_x(\omega) = \frac{2}{\pi} \int_0^\infty R_x(\tau)\cos \omega\tau \, d\tau \tag{4}$$

where $R_x(\tau)$ is the auto-covariance function defined by

$$R_x(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)x(t + \tau)dt \tag{5}$$

The power spectral density $\Phi(\omega)$ has the dimensions of "power" per radian per second and thus for the measurement of atmospheric turbulence depends upon the airplane forward speed. In order to express the power spectral density functions in terms independent of airplane flight speed, the change of variables

$$\Omega = \frac{\omega}{V} \tag{6}$$

is used. In the use of power spectral techniques to describe atmospheric turbulence it is assumed that the turbulence spacial pattern is invariant during the time of the airplane passage.

An additional property of significance is that the variance or mean square of the random disturbance is defined by

$$\overline{x^2(t)} = \int_0^\infty \Phi(\omega)d\omega \tag{7}$$

and represents a measure of the intensity of the disturbance. The value generally found in the literature, however, is the square root of the variance, the so-called root-mean-square value σ. In practical application the power spectrum can only be defined over a finite frequency range, and in the present paper the values of root mean square σ will refer only to this finite range.

The discrete and continuous turbulence methods are complementary in regard to airplane design problems and as a measure of the relative intensity of the turbulence, and both methods are being used in studies of airplane responses. In this paper, however, the discussion of the turbulence environment will be based generally on the continuous turbulence method.

FLIGHT CONDITIONS

The surveys of severe storms over the southwest in 1960 were made with a T-33 airplane instrumented as indicated previously for the measurement of continuous turbulence. The flights were made under the control of the FAA by use of equipment at an Air Defense Command site. A sketch of the radar return and the flight path for the storm investigated on May 17, 1960, is shown in figure 2. The figure depicts approximate conditions near the termination of the flight survey. Since the storm was developing during the survey, the radar echo is the maximum size observed and additional storm clusters are developing to the northwest along the squall line.

Five traverses were made through this storm at an altitude of approximately 39,000 feet on a north-south heading in a pattern indicated by the dashed lines and arrows on the figure. The magnetic heading for each traverse is given in table I. The traverses were through the area enclosed by the dashed lines through the echo outline, during a 38-minute time interval beginning at 1622 hours CST on May 17, 1960. During the flight survey the cloud diameter grew from 7 nautical miles to 21 nautical miles.

TIME HISTORIES OF GUST COMPONENTS

The time histories of the components of the true gust velocities for the first traverse through the storm of May 17 are given in figure 3.

The vertical components of the true gust velocities are shown in the upper trace and the horizontal components in the lower trace. In each case the velocities are plotted against time and distance. The time of cloud entry and cloud exit is indicated in the figure. It is noted that the time histories of vertical component begin and end at approximately -20 fps and the lateral component appears to have a linear trend from -70 fps at the beginning of the time history to +10 fps at the end of these traces. Neither of these beginning and end points may be real since such factors as gyro drift and the inability to establish initial and final conditions prohibits the exact location of the zero value and the elimination of very low frequency trends, i.e., frequencies approaching zero, in the time histories. The numerical values cannot be taken as absolute values, although in this paper the actual values obtained will be quoted.

For the vertical components, a positive gust is up and the positive lateral component is airflow toward the right of the airplane. Both the vertical and lateral time histories indicate an apparent random sequence of long and short wavelength disturbances throughout the clouds' horizontal extent. A predominant downward flow of air apparently existed near each edge of the cloud with upward flow in the center. A very close similarity of the two time histories exists at a time of 60 seconds where the large change in the lateral gust velocity is associated with an equally large change in the vertical gust velocity. The overall impression from these two time histories is that the horizontal flow is of a similar magnitude to the vertical flow, at least near the top of a severe convective cloud.

The derived gust velocities have been plotted at the top of the figure to give some insight into the interpretation of these values. It will be recalled from figure 1 that each value of U_{d_e} corresponds to a maximum or peak acceleration at the center of gravity of the airplane. A comparison of the derived gust velocities with the time history of the vertical component of gust velocity indicates a correspondence of the derived gust velocities with the sharp or short wavelength changes in true gust velocity. No correspondence is apparent with the long wavelength disturbances. These observations simply result from the airplane's response characteristics to atmospheric disturbances of various wavelengths. The T-33 airplane in general will experience the larger accelerations for eddies or gusts represented by the high-frequency fluctuations in the time history. The derived gust velocities therefore represent fairly well the high-frequency velocity changes, but do not give a measure of the velocities for the drafts or large wavelength disturbances.

The airflow at a much lower altitude in a different storm is shown in figure 4. The time histories represent the horizontal and vertical components of the gust velocities at 25,000 feet altitude which, in this case, is about 25,000 feet below the top of the clouds. Note that the histories represent about 6 miles of the traverse in the center of the storm and start about 12 miles after the storm entry. The frequency characteristics of the turbulence appear similar to those near the top of a cloud and the lateral components are again of the same general magnitude as the vertical components.

The maximum gust velocities noted on these figures vary between -118 feet per second and +66 feet per second. These maximum values and a summary for nine additional traverses made through the storms of May 4, 16, and 17, 1960, are tabulated in table I. This table contains information as to the dates, time of traverse, aircraft heading, etc. The May 16 storm is of interest because it is believed that the largest gust velocity measured to date occurred in this storm. Complete data, however, were not evaluated in time to be included in this paper. Note in table I a positive gust velocity of 208 feet per second and a negative velocity of 124 feet per second. At the time of the positive gust the airplane was in a pitched-down attitude of 13 degrees and had an upward vertical velocity of 83 feet per second. The vertical acceleration of the airplane at this instant, however, was only 18 feet per second per second. Hail was encountered on this traverse which left a dent of baseball size on the airplane.

SEVERE STORM TURBULENCE

Before considering in more detail the turbulence intensities within the storms in the Oklahoma area, let us first compare some turbulence measurements for several weather conditions as a means of forming a basis for interpreting the turbulence intensities. The spectra of turbulence for average clear-air turbulence conditions, turbulence in cumulus clouds, and in severe storms are shown in figure 5. The power $\Phi(\Omega)$ is plotted against reduced frequency Ω in radians per foot and wavelength l in feet. A logarithmic scale is used in each case. The least severe turbulence is shown by the curve on the left and the most severe turbulence, for the thunderstorm or squall-line condition, appears on the right. The square roots of the areas under these spectra are the rms gust velocities and are used as a convenient measure of turbulence intensity. The rms gust velocities are 3.48, 6.14, and 13.77 feet per second for the samples of clear air, cumulus cloud, and the thunderstorm turbulence, respectively. These rms values can vary considerably for different traverses through a given type of turbulence, as for example, the rms gust velocities for traverses through storms in the 1960 operations of the National Severe Storms Project have varied from 6.14 to 16.02 feet per second.

It might be noted that the spectra all cover a range of wavelengths from about 3,600 feet to 60 feet, or 1/6 to 10 cps. The data falling within this frequency band are considered to be quite good for the present results. Extensions of the data to higher frequencies are limited by a number of considerations such as film speed and recording time available and the reading interval required, and, of course, the frequency response of the flow vanes or other instruments. Extensions to lower frequencies are limited by such factors as gyro drift, and establishment of initial and final conditions and zeros with the required accuracy for integration. Since the spectra have not been extended below a frequency of 1/6 cps, the rms gust velocities given above and obtained from the areas under these spectra do not contain the effects of power below 1/6 cps. The sample time histories presented earlier, however, are believed to give fairly reliable indications of the vertical and lateral air motions at frequencies considerably lower than 1/6 cps.

Distributions of derived gust velocities which have also been commonly used in describing turbulence are given in figure 5(b). These distributions also represent clear air, cumulus clouds, and thunderstorms. The storm conditions are representative of the data obtained from the 1946-1947 thunderstorm project (ref. 4).

Variation of Turbulence With Time

The turbulence spectra for five traverses through the storm on May 17, 1960, are shown in figure 6. The traverses were made in a north-south direction as indicated earlier at an altitude of 39,000 feet. The storm was building during the time of the flight so that the first traverse at 1622 hours CST was 7 miles in length in the cloud while the last traverse, approximately 34 minutes later, was 21 miles in length. The spectra for traverses 1, 2, and 4 are very similar in shape and intensity. The rms gust velocities for these traverses are 16.0, 13.6, and 13.8 feet per second, respectively. The rms gust velocities of 7.5 and 8.6 for traverses 3 and 5 indicate a reduction in power from the other three traverses. It is unfortunate that this variation in the power cannot be attributed entirely to pulsations of the cloud, but is believed to be in part due to slightly different flight paths through the storm. Traverse 3 definitely appeared to be nearer to the eastern edge of the heavy precipitation area as shown by the radar echo than did any of the other traverses.

Since the effect of the variables of time and flight path cannot be completely separated in this relatively small sample of turbulence data, it may be enlightening to consider the turbulence data in reference to the length of flight paths within the cloud. Figure 7 shows both values of rms gust velocity and the cloud diameter plotted against time from the beginning of the first traverse. The values of the rms gust velocities illustrate the variation in the intensity of turbulence with time as previously discussed. The level of turbulence for all the traverses is relatively high, however, with a mean rms value of about 12 feet per second. The plot of cloud diameters indicates that the cloud was growing rapidly at the beginning of the traverses with a diameter of 7 miles for traverse 1 and 16 miles for traverse 2. This period of activity seems to be followed by a period of little growth with the diameter remaining unchanged but with the turbulence intensity decreasing for traverse 3. The last three traverese indicate a second cycle of growth with a corresponding increase and decay in the turbulence level.

Turbulence at Different Altitudes

Now let us consider the turbulence at different altitudes. In figure 8 are the spectra of turbulence for traverses at 40,000, 35,000, 30,000, and 25,000 feet altitude through a storm on May 4, 1960. The first traverse began at 1547 hours CST for the highest altitude and the last traverse started 36 minutes later for the lowest altitude. These cloud surveys were made on approximately east-west headings and the cloud traverses were approximately 22 nautical miles in length except for a 30-mile traverse at 35,000 feet altitude.

The figure indicates that this storm contained less severe turbulence than the storm of May 17, 1960. For the penetrations made, the most severe turbulence occurred at 40,000 feet altitude with relatively constant but less severe turbulence at the lower altitudes. The rms values are 9.73, 6.64, 6.14, and 6.48 feet per second for the highest to the lowest altitudes, respectively.

From the spectra of turbulence it is not possible to attribute the change in the turbulence intensity specifically to the altitude change because of the time variation between the traverses. Since the cloud dimensions did not vary appreciably with time, it may be assumed that the cloud had reached its mature stages before the traverses were made.

The spectra of horizontal gust velocities are very similar to the spectra of vertical gust velocities for each traverse evaluated. The similarity applies to both the shape of the spectra and the energy content. It may be concluded, therefore, in a general sense, that there is as much horizontal flow as vertical flow in the storms for the ranges of wavelengths covered by the spectra.

ATMOSPHERIC PRESSURE VARIATIONS

The instrumentation in the test airplane, although designed to measure atmospheric turbulence, yielded measurements which could be used to investigate the variation of atmospheric pressure within the storms. It was felt that these measurements of the variation of the pressures may be of value in future studies of the dynamics of the storms. These pressure changes are commonly called "D" values and are presented as the correction in feet of altitude which must be added to the measured pressure altitude to determine the true altitude.

Incremental "D" values were determined for the two storms on May 4 and May 17. The word incremental is used because an arbitrary starting point, the condition just before entering the cloud, was used. In the evaluation of the "D" value it is assumed that the pressure is invariant for all positions around the cloud and that the true displacement of the airplane within the cloud is given by the inertial determination of the airplane displacement (from double integration of the vertical accelerations). The integration of the vertical acceleration was performed assuming that the initial and final vertical velocities of the airplane are equal, and the "D" values are constant at cloud entry and exit. It was not possible to separate changing "D" value from changing altitude at the starting and ending points; however, the sum of the two was, in each case, fairly small. These assumptions can lead to some error in the magnitude of the "D" values. With these precautions, the incremental "D" values for the five traverses on May 17 are presented in figure 9(a) and the values for the May 4 storm are presented in figure 9(b). In each figure the "D" values are plotted against approximate time from cloud entry.

It is apparent from an inspection of figures 9(a) and 9(b) that the "D" value may vary over a relatively large range, say, from +1,000 feet to -1,000 feet, and may change sign within a given storm. Figure 9(a) indicates that for the active storm of May 17 the "D" value was generally positive which corresponds to a greater pressure in the storm than in the surrounding atmosphere. These values were obtained near the top of a storm - at 40,000 feet in a cloud extending to approximately 45,000 feet altitude.

For the storm of May 4 the "D" values are generally negative for the several altitudes investigated. Earlier considerations indicated that this storm was matured or had ceased building at least during the flight investigation. Since the data from only one storm in this state of development are available, it is impossible to determine if this is a definite characteristic for the storm condition.

CONCLUDING REMARKS

In conclusions, the several observations discussed in the body of the paper may be summarized as follows: First, substantial vertical velocities, as large as 200 feet per second, can exist in severe storms. Second, the intensity of the turbulence may vary considerably from storm to storm, but the higher-intensity turbulence appears to be associated with periods of rapid growth of the storm cloud. Third, the horizontal components of the gust velocities for the storms investigated are of approximately the same magnitude and energy content as the vertical component of gust velocity for the frequency range considered herein. This similarity in components appears to be true even for altitudes 20,000 to 30,000 feet below the top of the cloud. Lastly, the pressures within the storms may vary widely and may be higher or lower than the surrounding atmosphere.

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TABLE I

SUMMARY OF TURBULENCE DATA FOR SOME STORMS IN 1960

Date	Time, CST	Traverse, number	Heading, deg	Altitude, ft	Altitude of cloud tops, ft	Max w_g, fps		Max v_g, fps		σ_{w_g}, ft/sec
						+, up	-	+, rt	-	
May 4	1548	1	240	40,000	Over 40,000	56	62	79	59	9.73
	1604	2	70	35,000		51	78	47	70	6.64
	1615	3	240	30,000		44	38	67	50	6.14
	1623	4	70	25,000		92	31	84	64	6.48
May 16	1724	1	190	38,000	42,000	141	105	104	146	15.55
	1736	2	350	40,000	50,000	208	124	87	93	15.38
May 17	1622	1	180	39,000	45,000	66	118	45	115	16.02
	1629	2	220	39,000		73	97	107	82	13.62
	1642	3	190	39,000		47	49	55	59	7.46
	1651	4	350	39,000		131	98	100	79	13.77
	1656	5	170	39,000		47	52	---	---	8.57

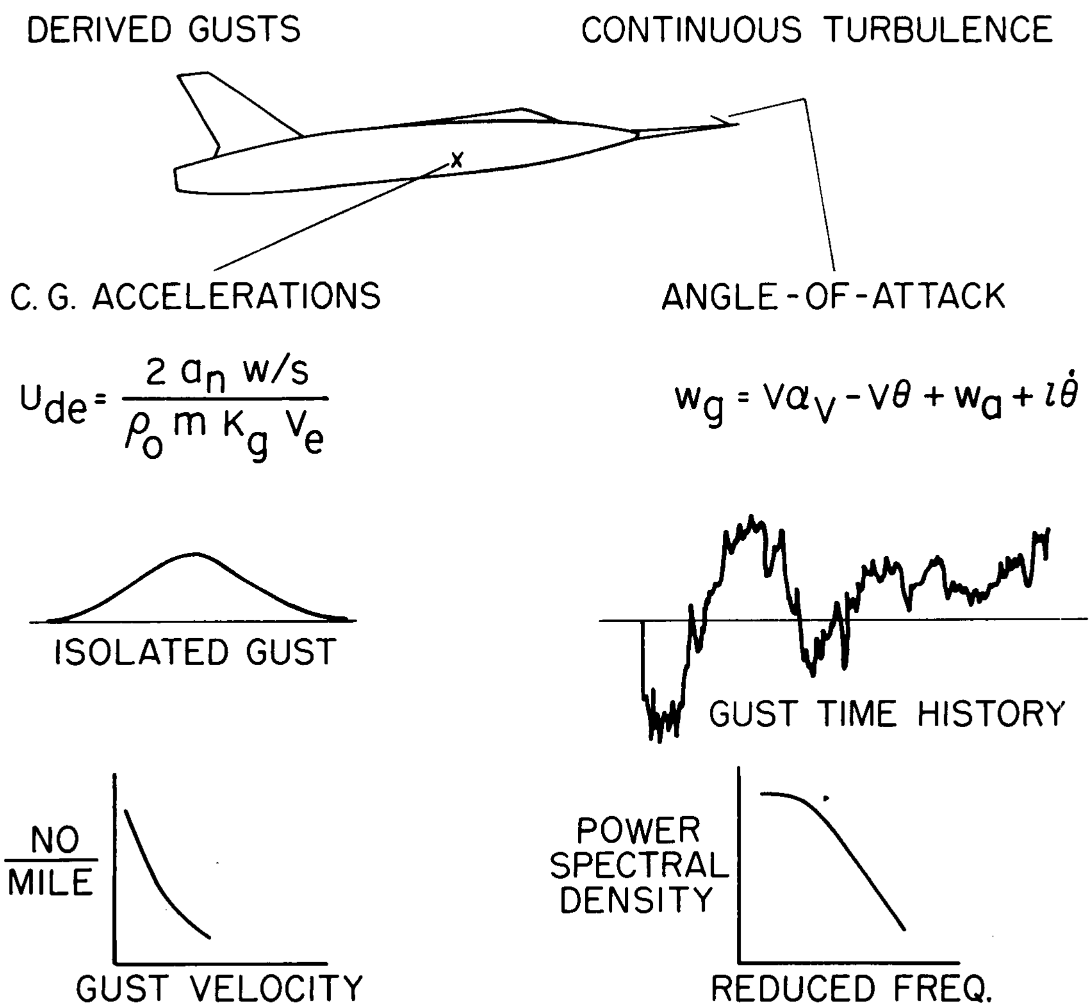

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Figure 1.- Methods for measuring and describing atmospheric turbulence.

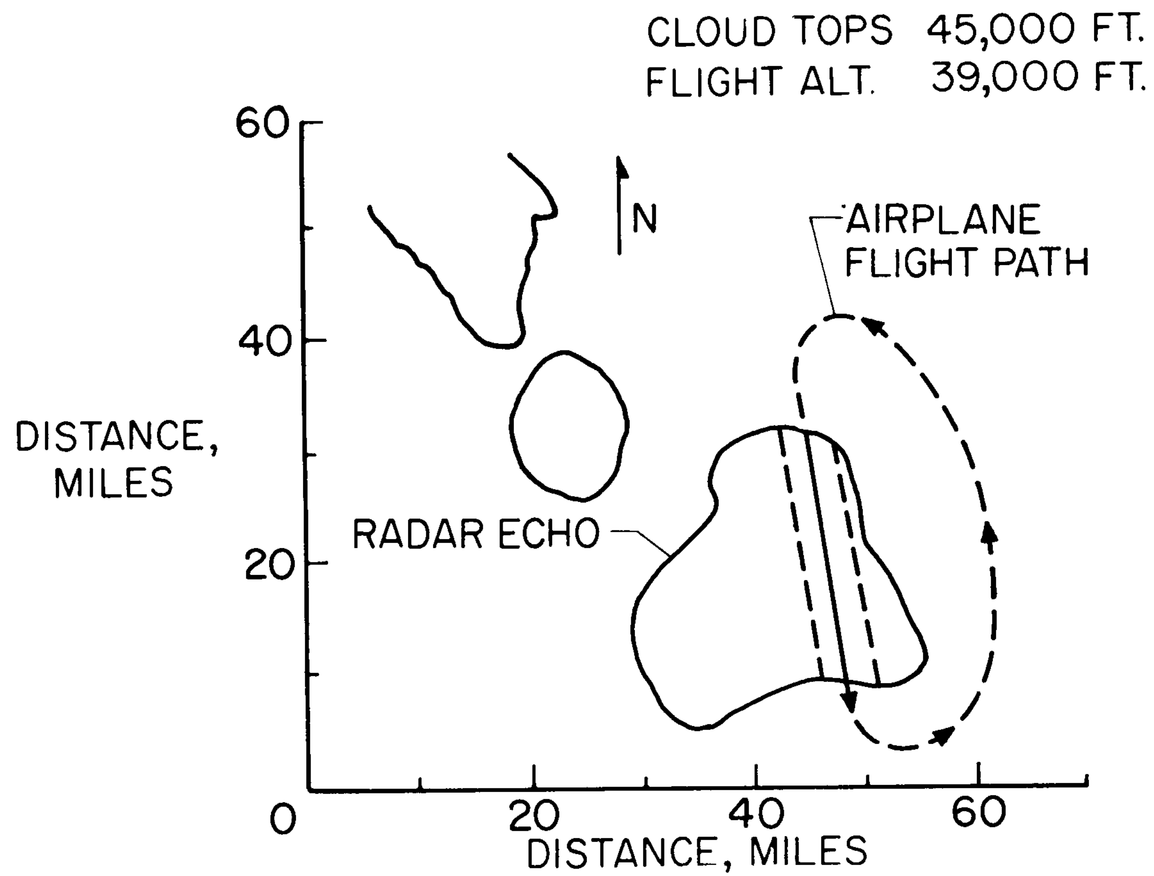

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Figure 2.- Sketch of thunderstorm radar echo and approximate location of traverses.

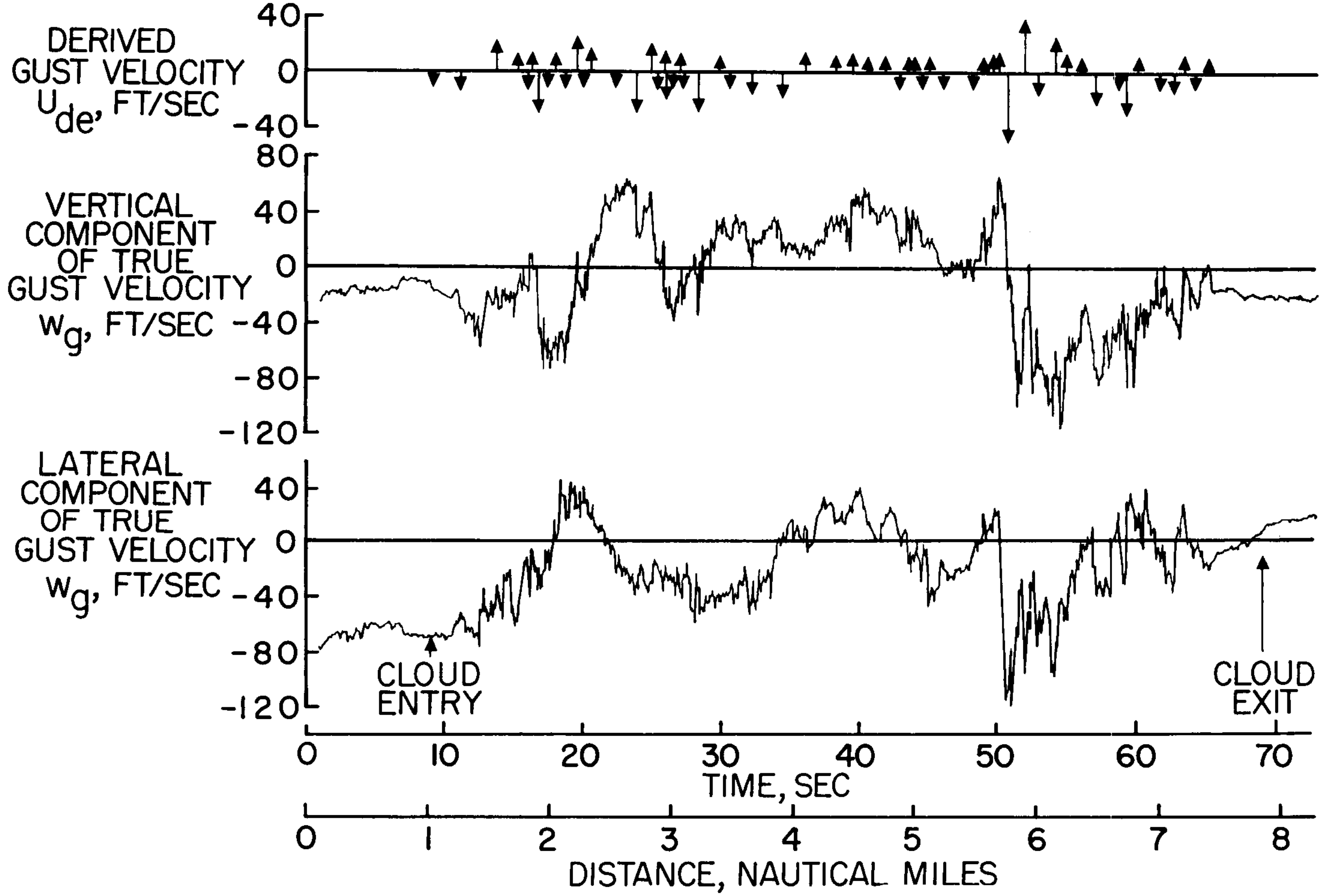

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Figure 3.- Derived gust velocities and time histories of vertical and lateral gust components, traverse 1 at 39,000 feet, May 17, 1960.

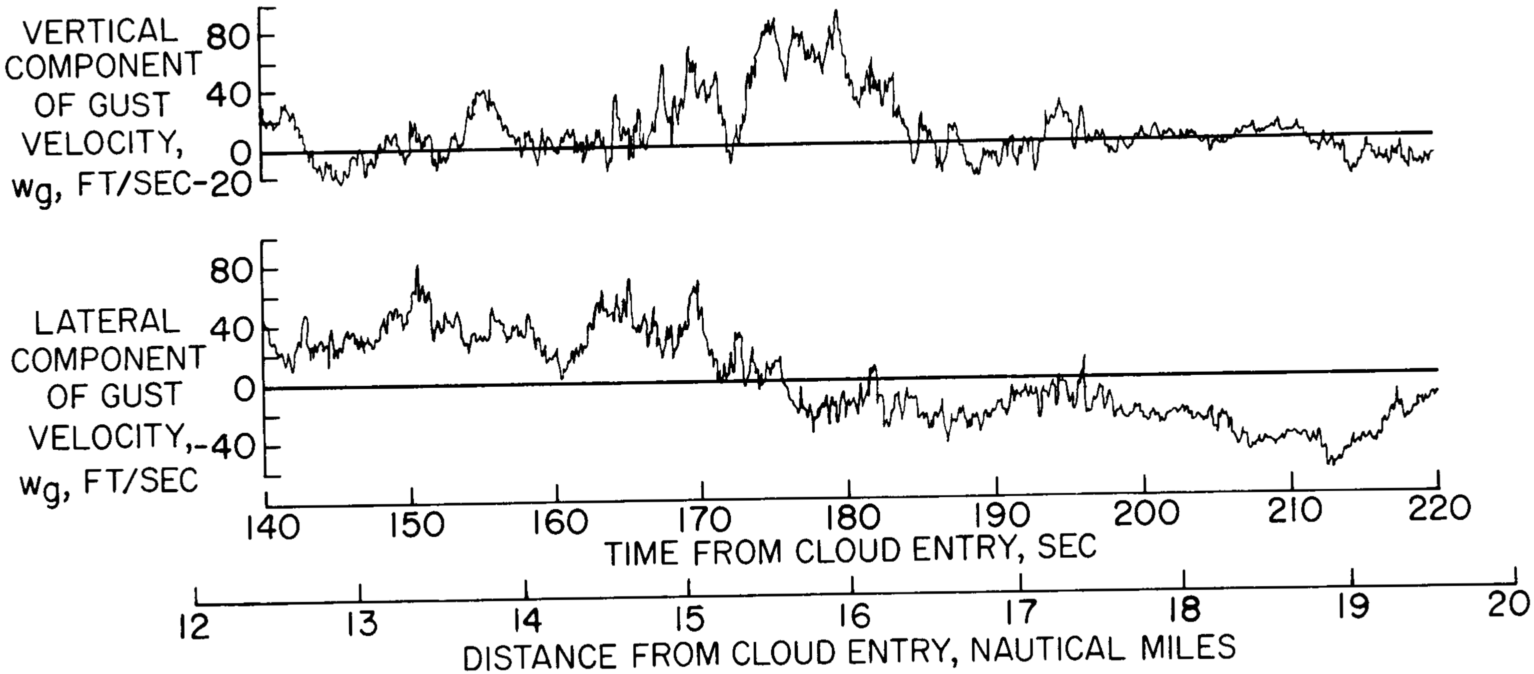

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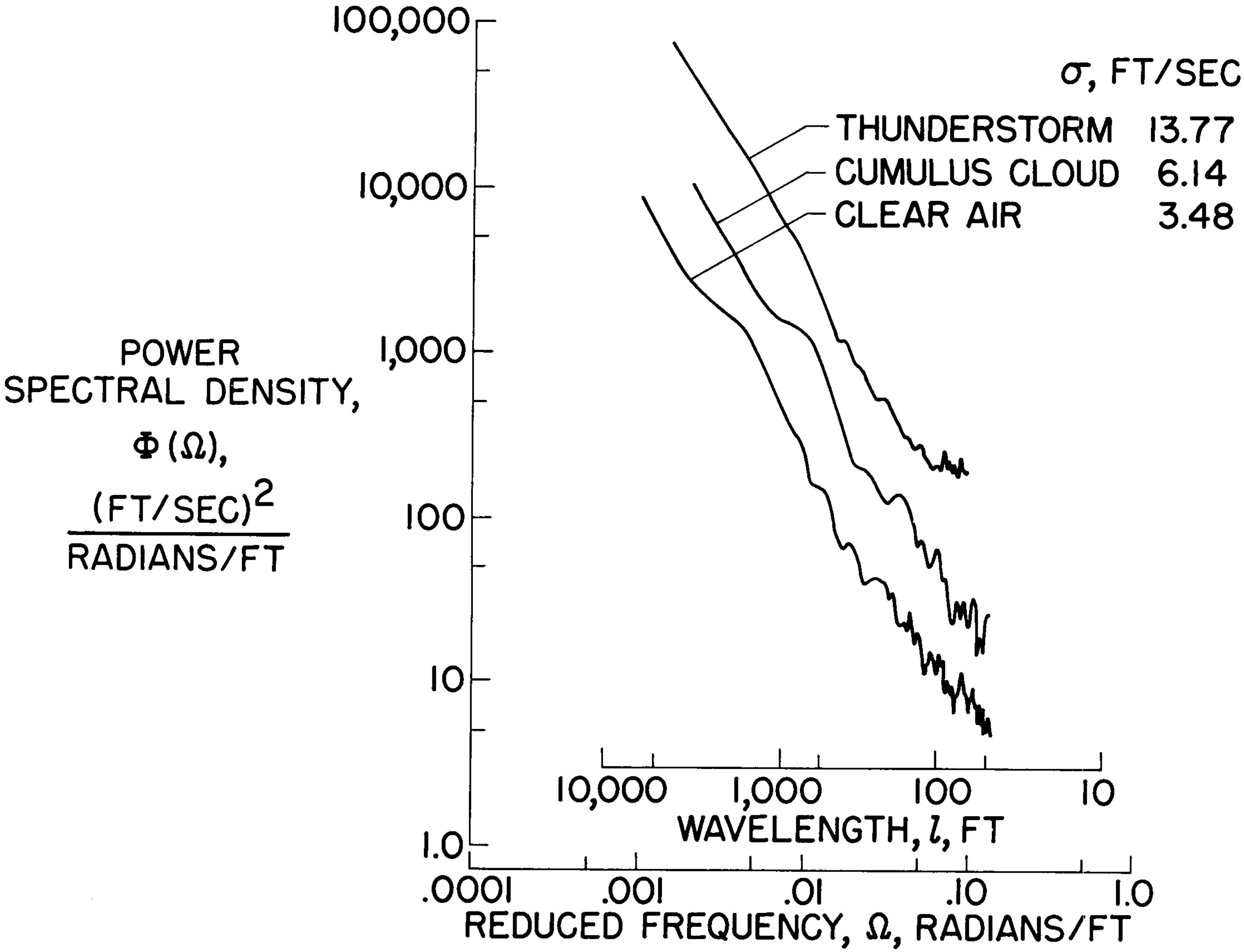
Figure 4.- Portion of time histories of vertical and lateral gust components, 25,000 feet, May 4, 1960.



(a) Power spectra.

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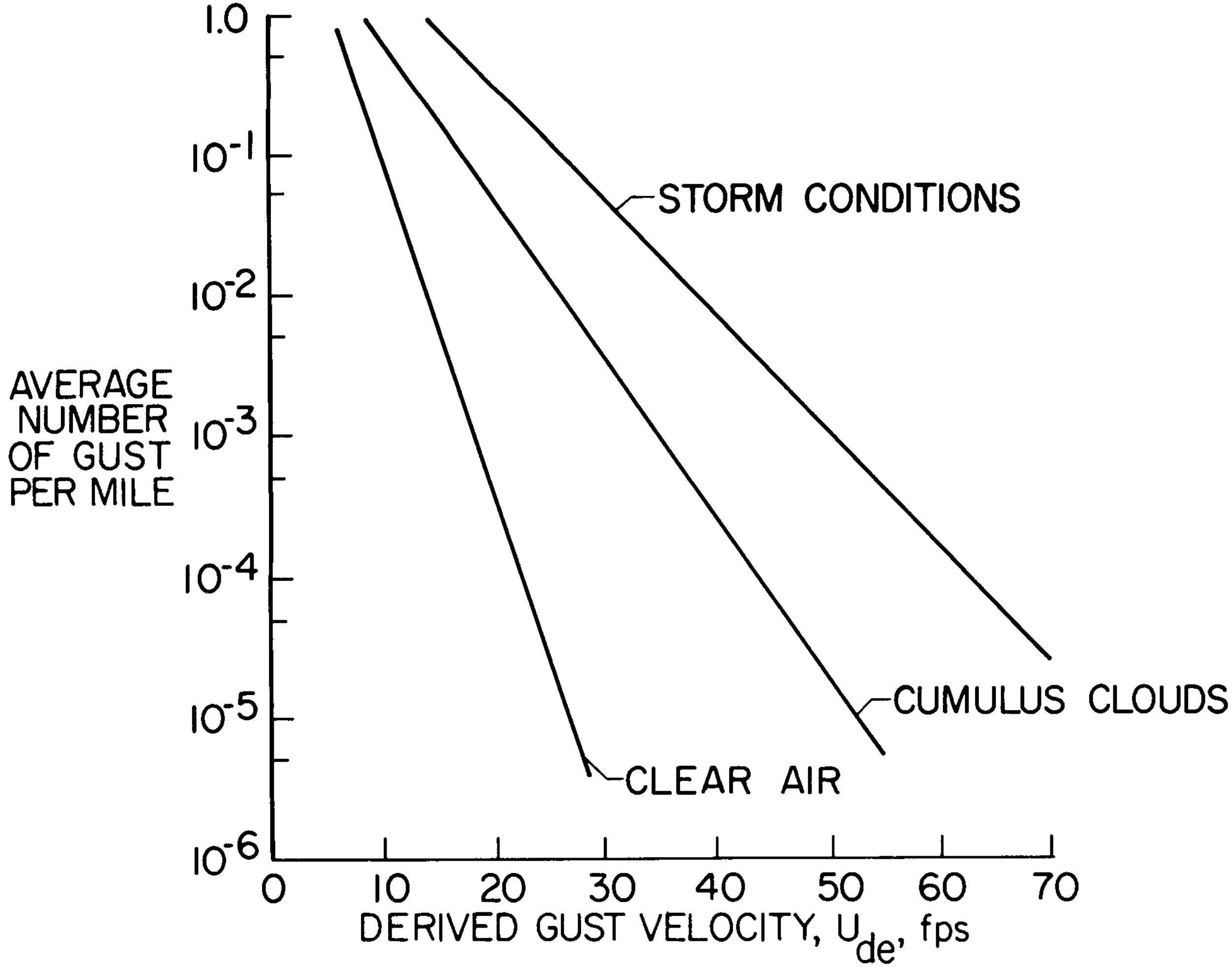
Figure 5.- Comparison of intensity of turbulence for three weather conditions.



(b) Derived gust velocities.

Figure 5.- Concluded.

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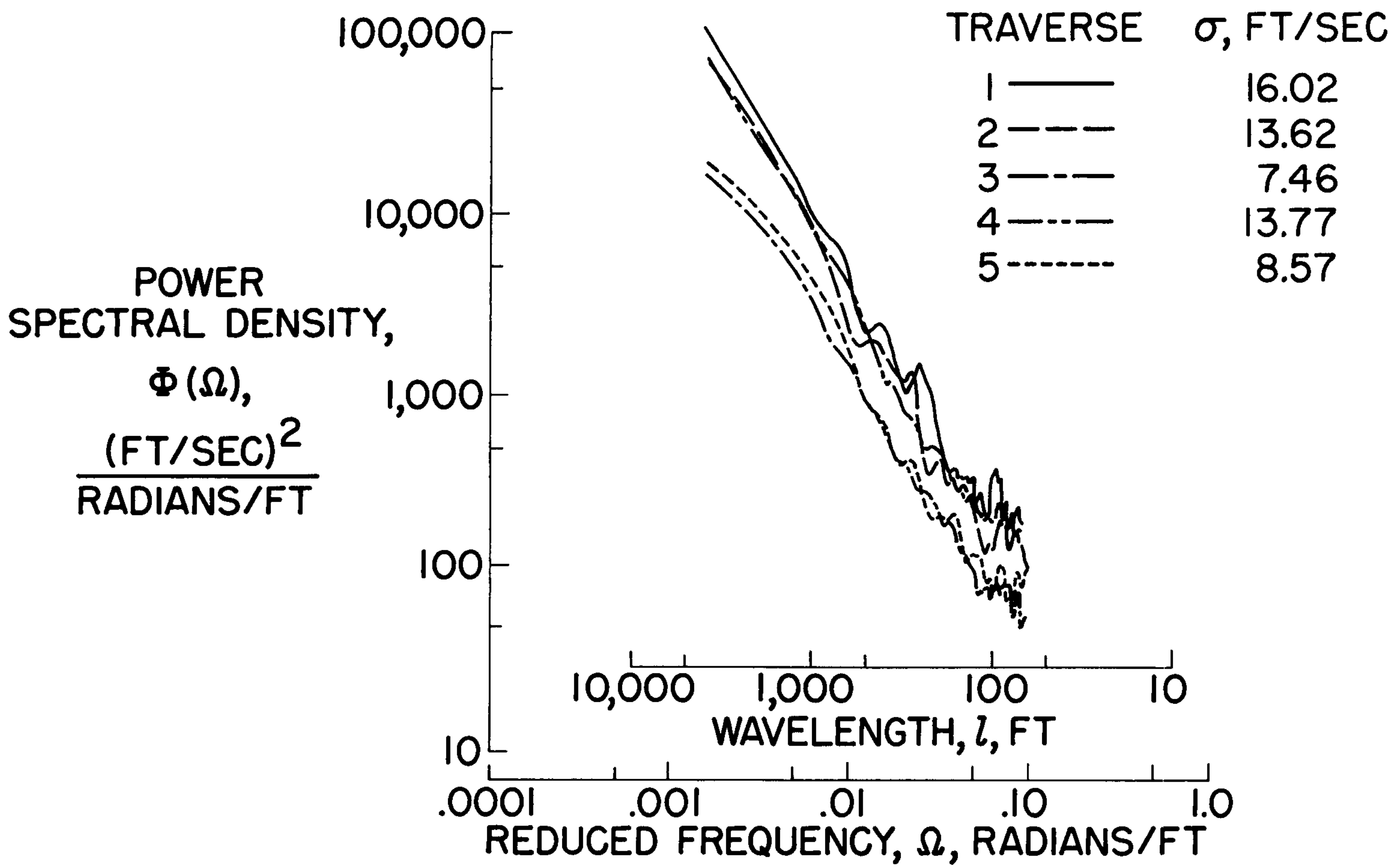

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Figure 6.- Comparison of power spectra of the vertical component of turbulence measured in successive traverses of thunderstorm, May 17, 1960, 39,000 feet altitude.

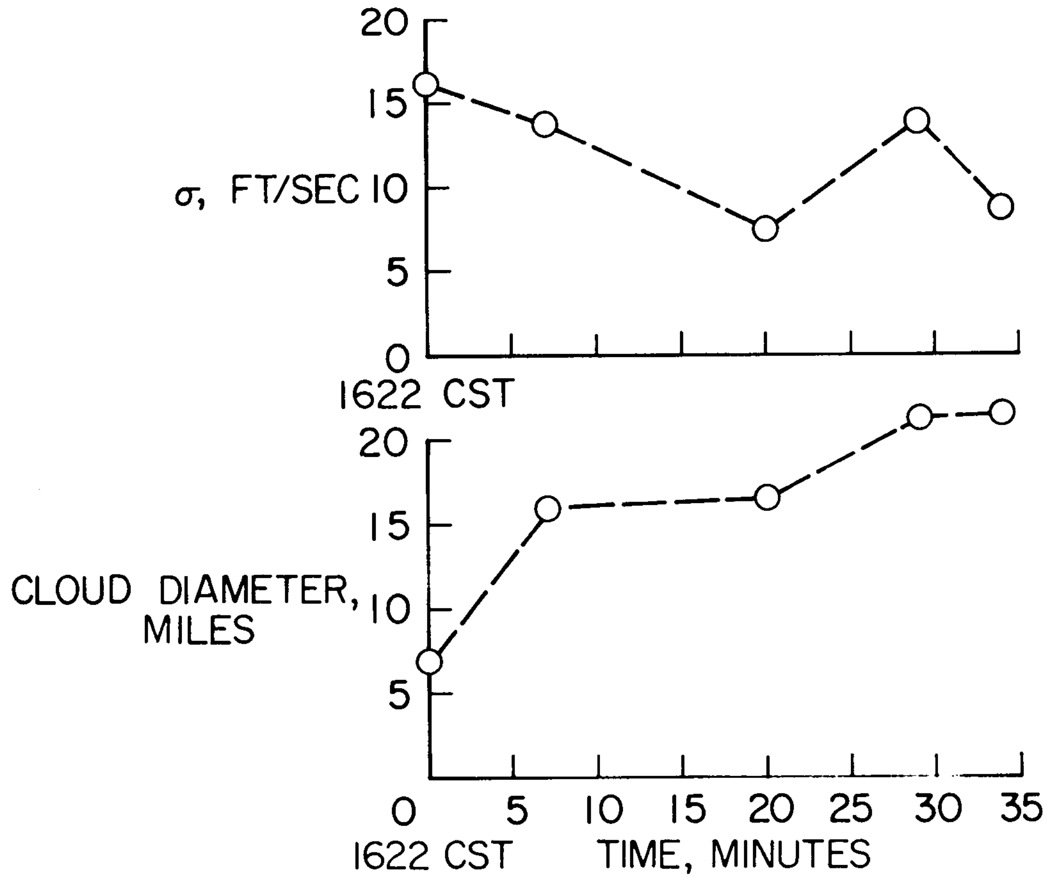

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Figure 7.- Variation of turbulence intensity and cloud diameter with time, at 39,000 feet altitude, May 17, 1960.

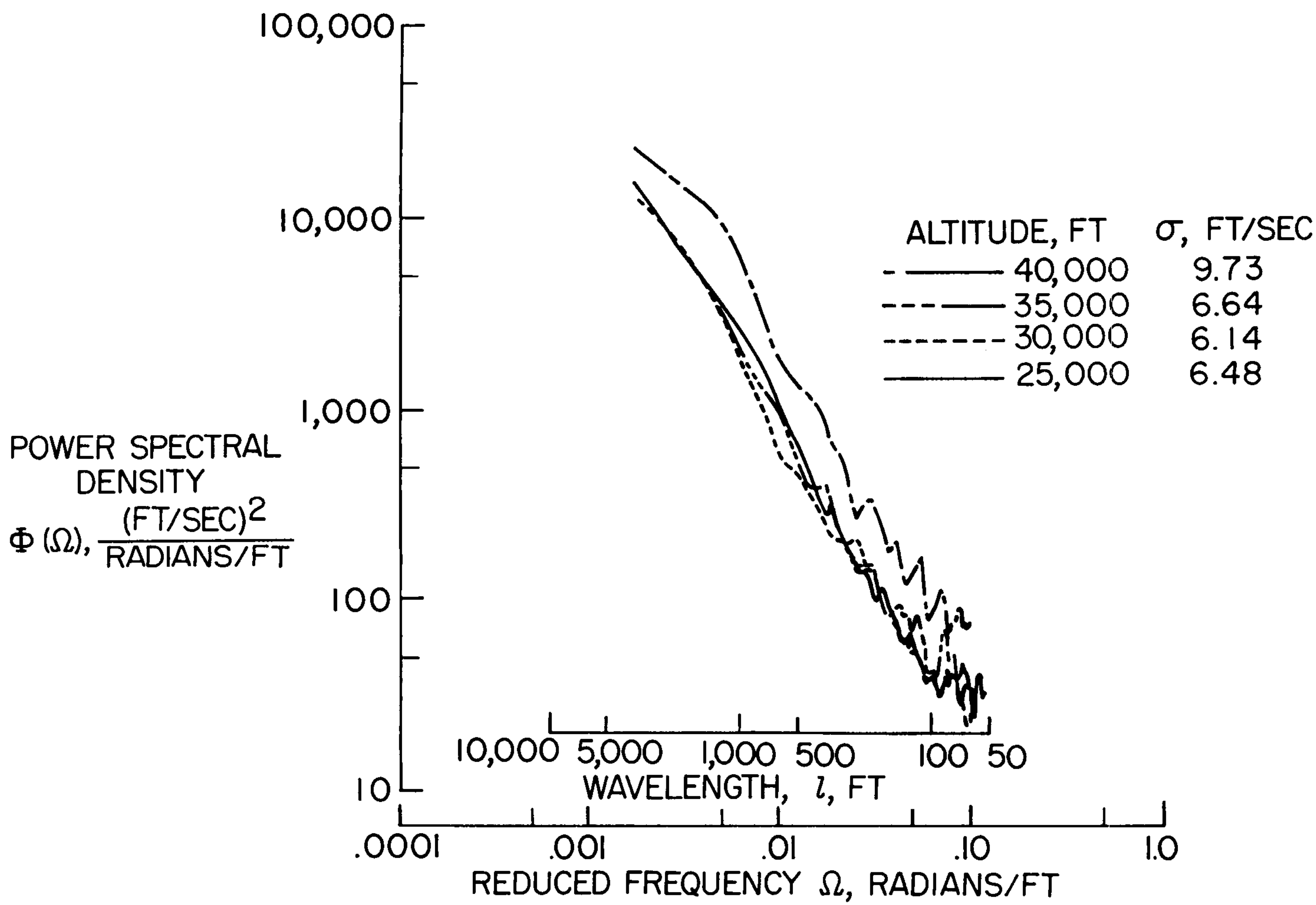

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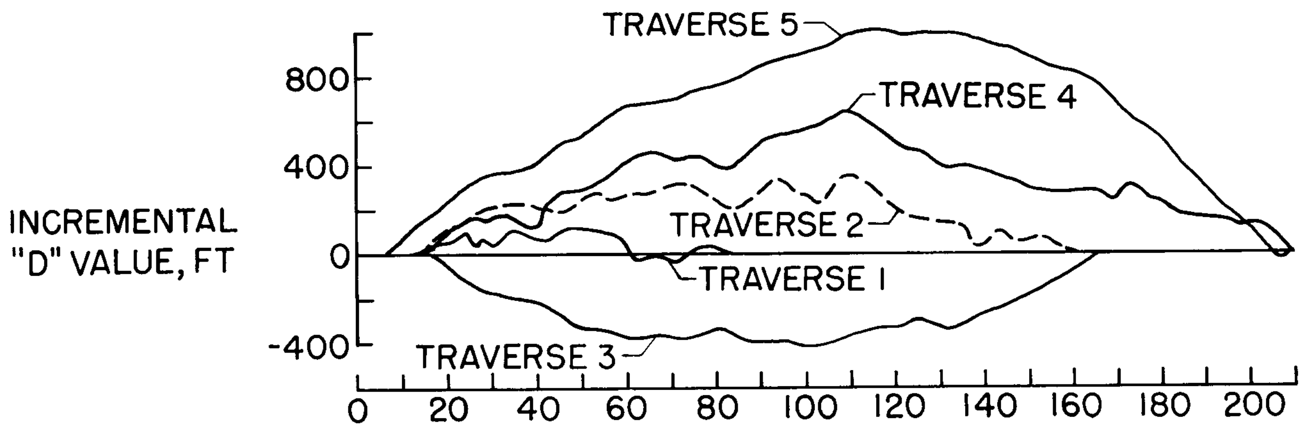
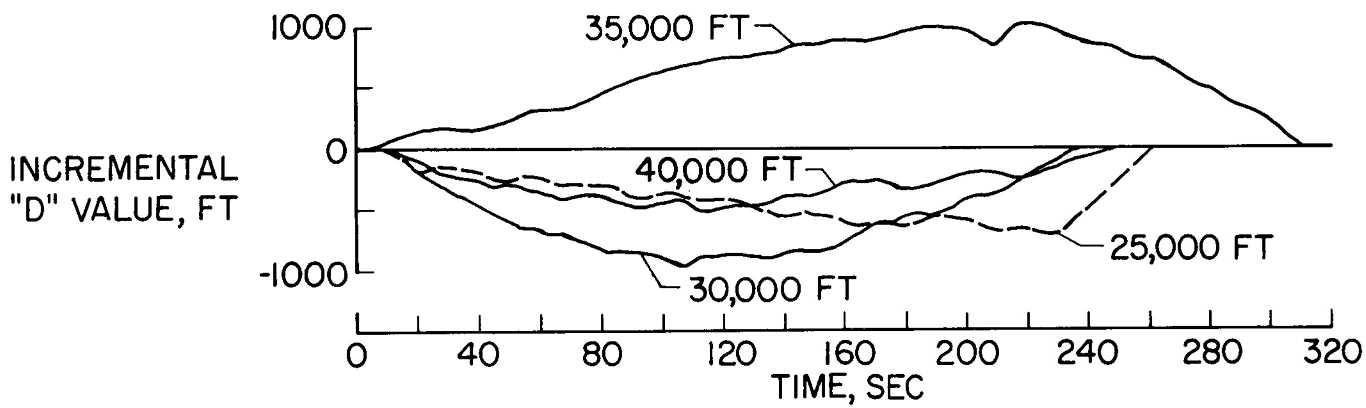
Figure 8.- Comparison of power spectra of vertical component of turbulence measured in successive altitude traverses of thunderstorm, May 4, 1960.



(a) Storm of May 17, 1960, 39,000 feet altitude.



(b) Storm of May 4, 1960.

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Figure 9.- Incremental "D" values within thunderstorms.

NASA-Langley, 1962